

Integrated Cross-Layer Protocols for Adaptive Transmission and Routing of Multimedia Traffic in Tactical Spread-Spectrum Networks

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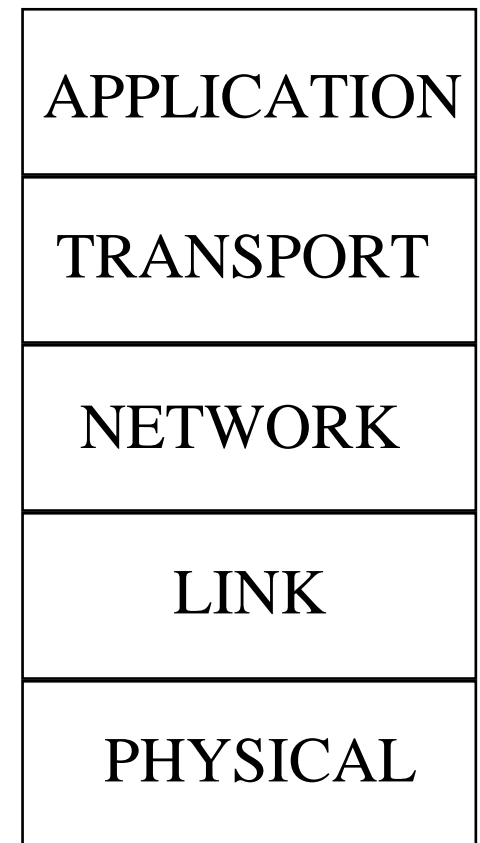
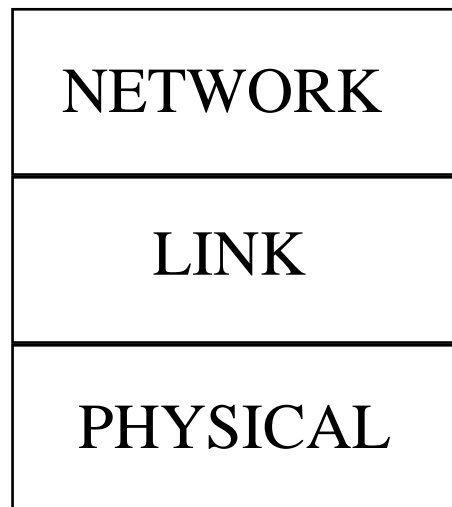
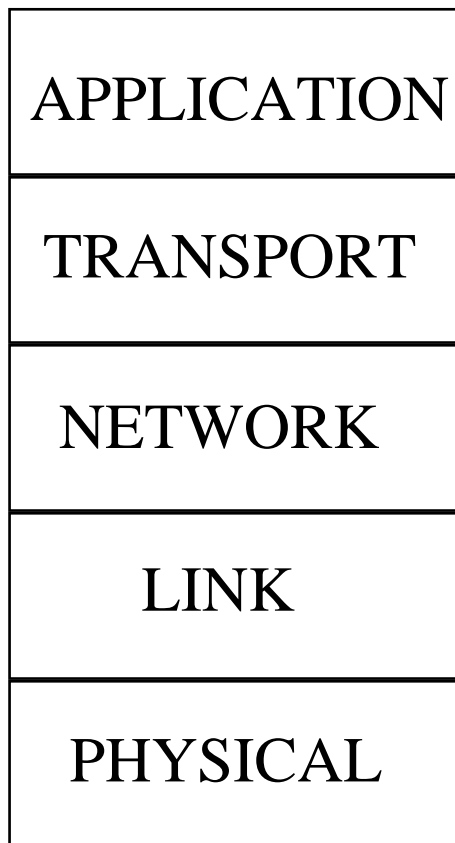
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Simplified OSI Network Model

Source

Relay

Destination

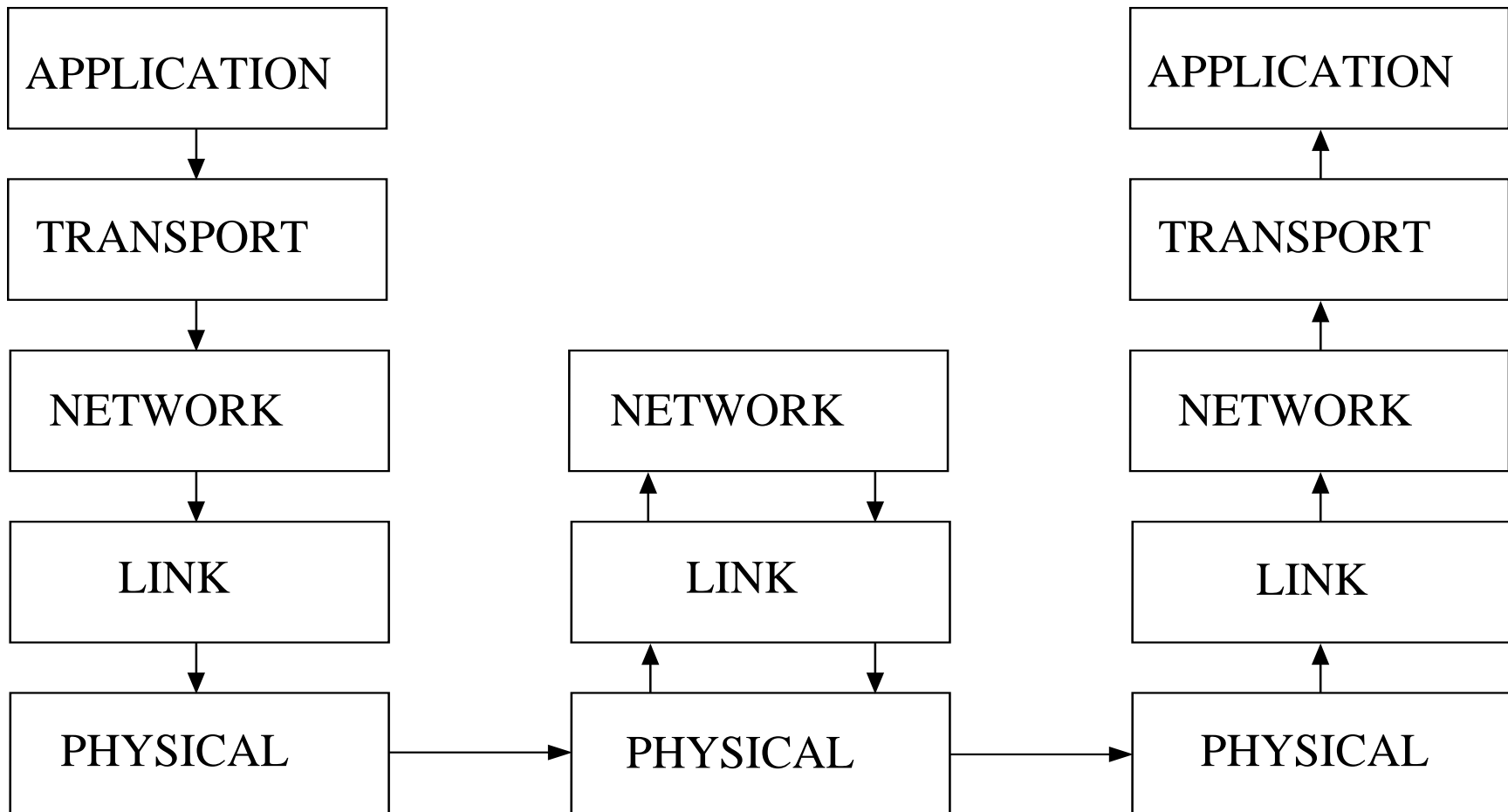


Traditional View

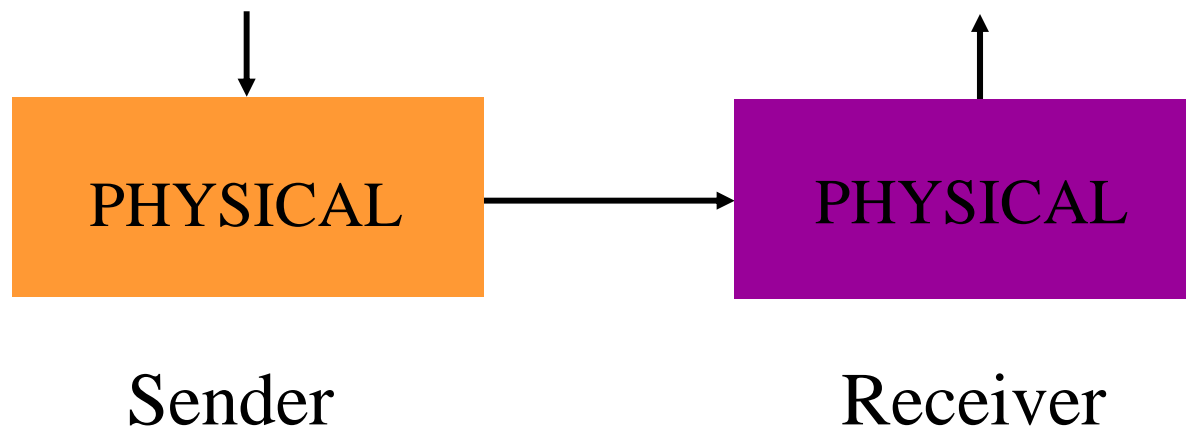
Source

Relay

Destination



The Bit Pipe



The Need for Cross-Layer Protocols: A Voice Message Example

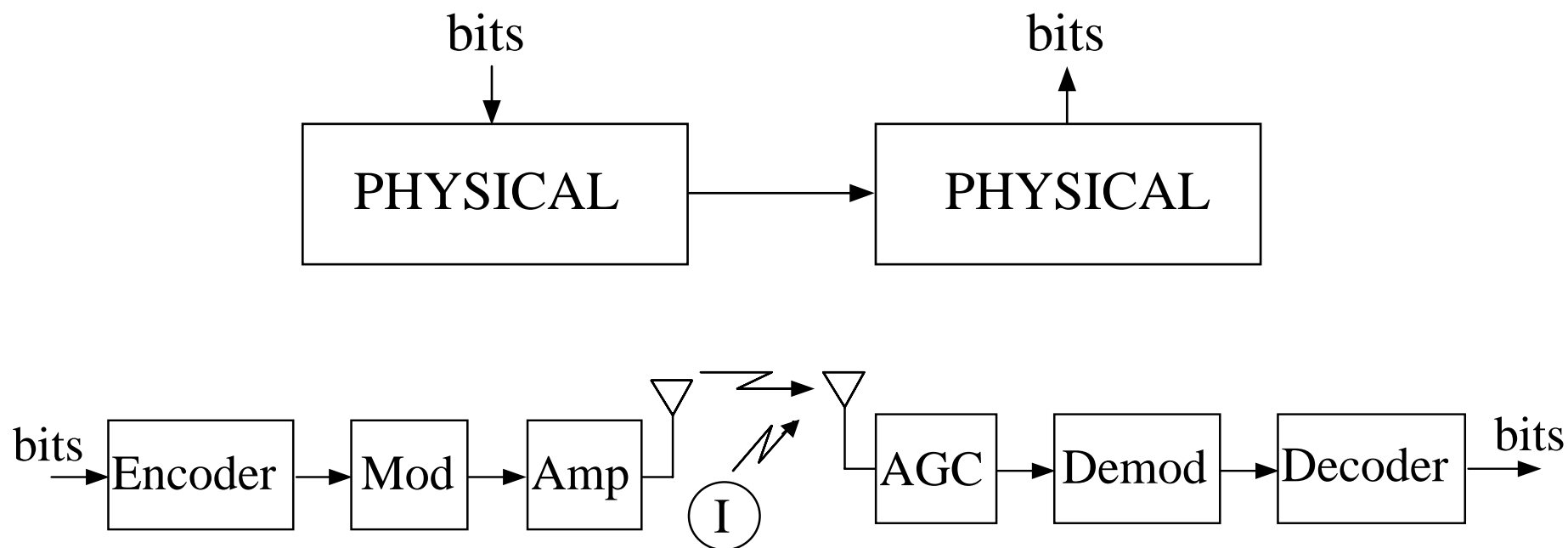
- Require low delay, some frame erasures acceptable
- Application layer: Speech compression must match available routes and links and satisfy QoS needs (intelligible speech vs. speaker recognition, etc.)
- Network layer: Routing should emphasize delay, high-quality (low bit error rate) routes not needed
- Link layer: Reserve multiple time slots on each link via the channel access (MAC) protocol. Detected errors may not result in a retransmission.
- Physical layer: Low-rate codes on poor links (avoid retransmissions), high-rate codes on good links (reduce delay), energy conservation secondary

Cross-Layer Protocols: The Previous Millennium

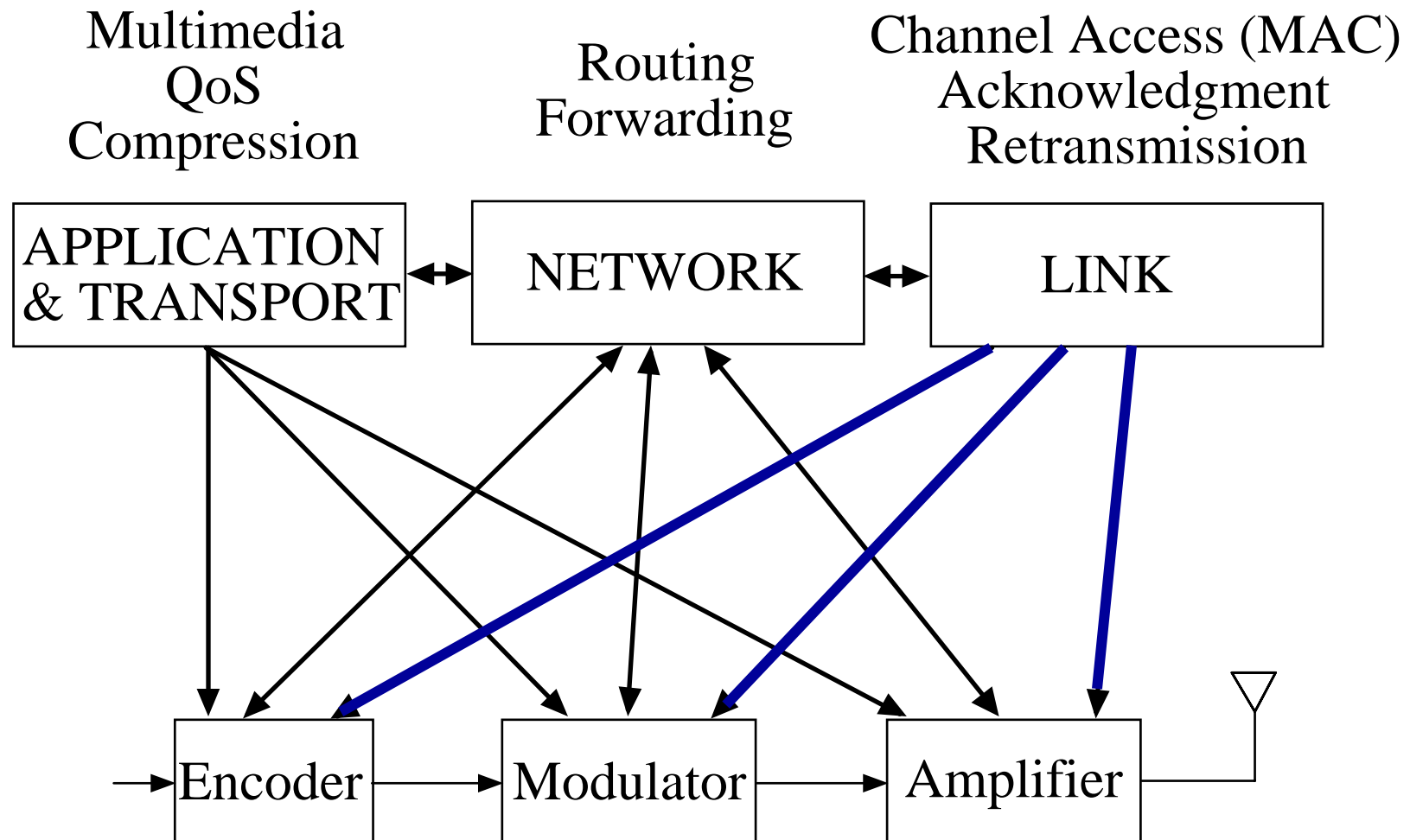
Terminology (early 1980s to late 1990s):

- Interaction between network operation and the communication subsystem
- Interaction between layers in the network model
- Interplay between spread spectrum and network protocols
- Network layer issues merging with link layer issues
- Interactions between the network layer and the link and physical layers in a spread-spectrum radio network
- Integration of physical-layer information into routing protocols; use of receiver side information in routing
- Tightly coupled protocols; interactive protocols; integrated protocols
- No particular name or phrase; layers simply ignored

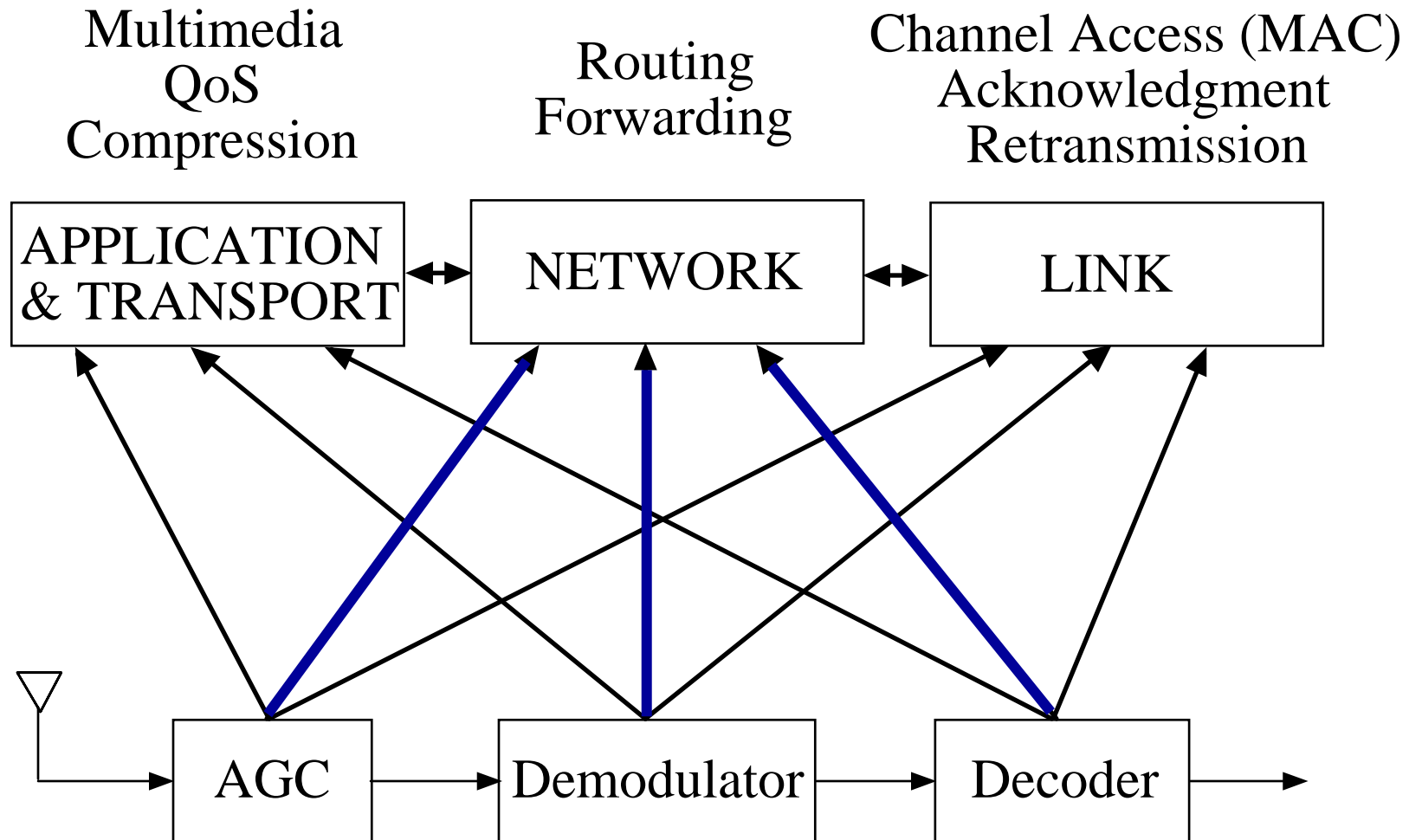
A Look Inside the Bit Pipe for Wireless Communications

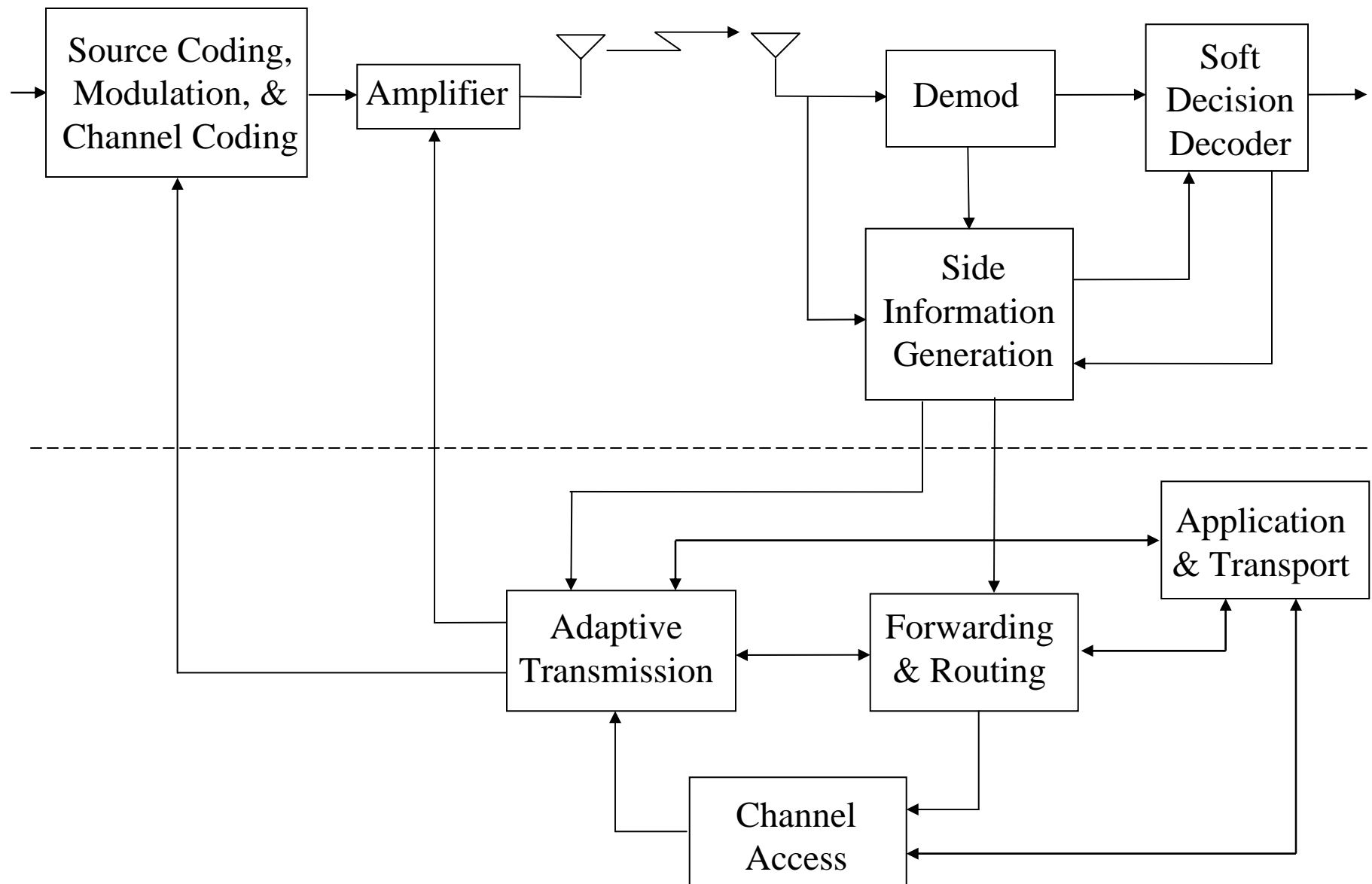


Some Interactions with the Sender's Physical Layer



Some Interactions with the Receiver's Physical Layer



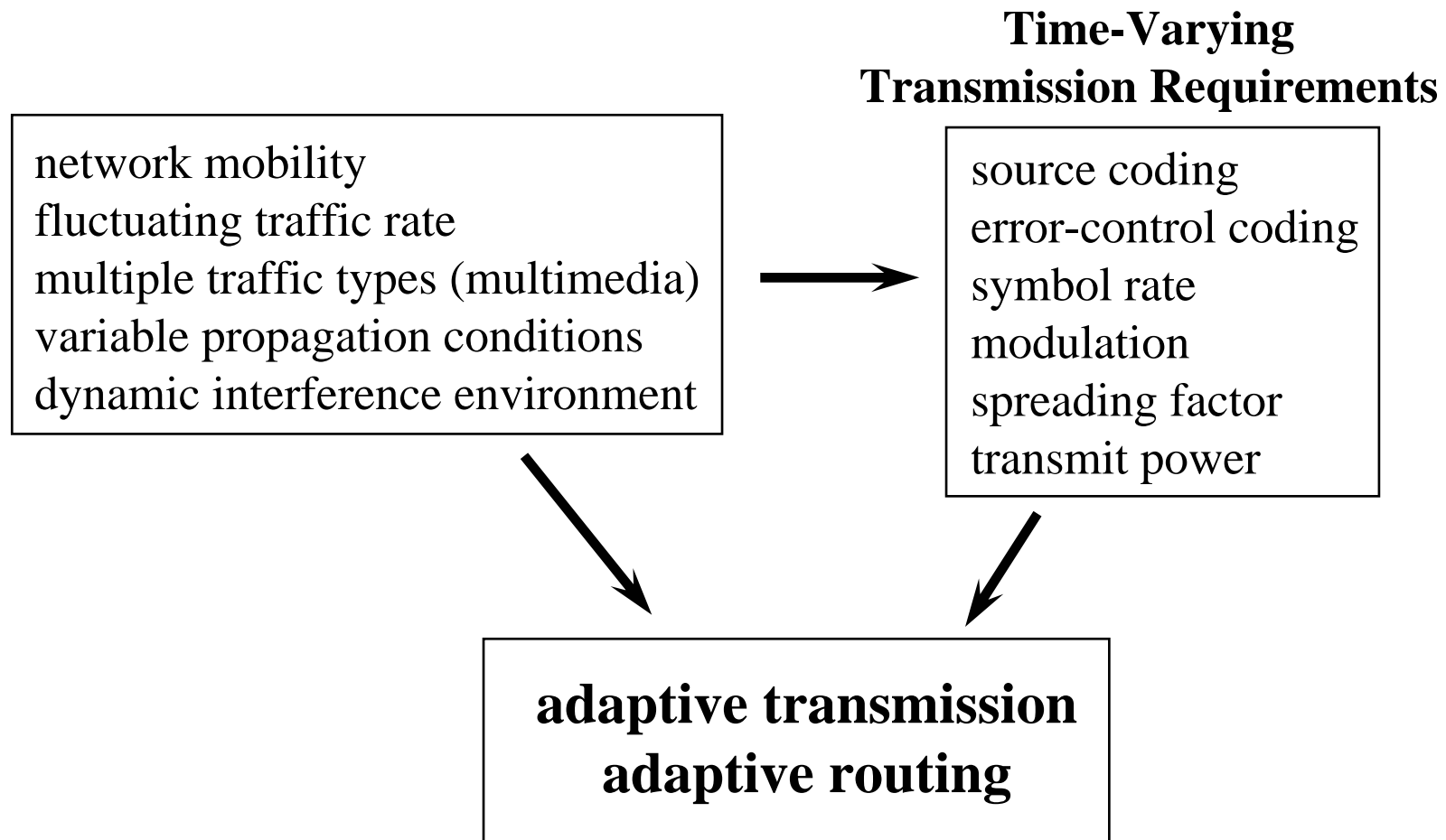


Some of the Protocol Interactions

Network and Traffic Characteristics

- Multiple-hop wireless spread-spectrum network
 - Store-and-forward relaying of packets required
 - Network must conserve energy (e.g., number of batteries)
- Frequency-hop or direct-sequence spread spectrum
- Dynamic environment
 - Variable propagation
 - Time-varying interference
- Multimedia traffic of three types
 - Delay-sensitive traffic, perhaps error-tolerant (e.g., voice)
 - Delay-tolerant, error-intolerant traffic (e.g., data)
 - Delay-tolerant, error-tolerant traffic (e.g., imagery)

The Need for Adaptivity



Efficient Handling of Multimedia Traffic

- Adaptive transmission protocol
 - reduce energy and on-air time for delay-tolerant messages (e.g., decrease power, increase code rate)
 - increase reliability for delay-sensitive messages
- Adaptive routing protocol
 - conserve energy for delay-tolerant messages
 - sacrifice energy conservation for delay-sensitive messages

Cross-layer protocols for adaptive transmission and energy-efficient routing of multimedia traffic

Goals of Adaptive Transmission and Routing

- Make each communication link as energy and time efficient as possible
- Minimize detectability and interference for unintended recipients
- Supply routing protocol with energy-efficient paths
- Select routes that exploit differences in QoS requirements to conserve energy

Adaptive Transmission in Tactical Networks

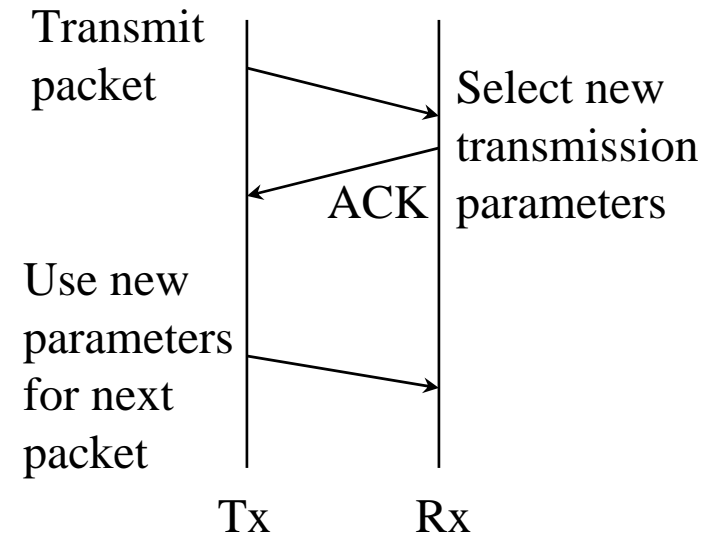
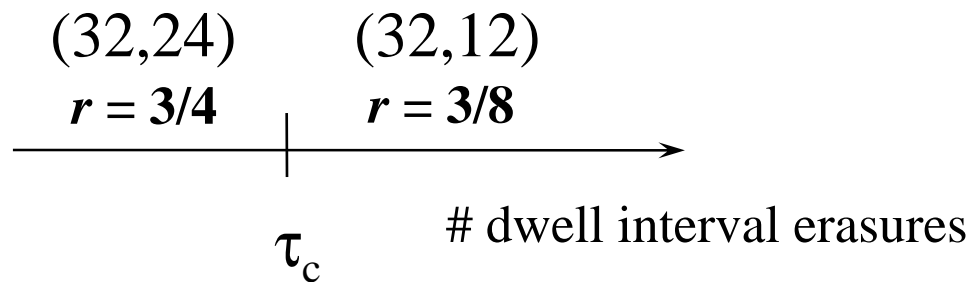
- Half-duplex radios: Feedback opportunities limited to ACK packets, reservation replies, control packets, etc.
- Channel adaptation: Primarily for such phenomena as changes in range, shadowing, and interference (not fast fading)
- QoS adaptation: Primarily for changes in QoS requirements from message to message when handling multimedia traffic
- Adapt to improve reliability when channel conditions deteriorate or when required for QoS
- Adapt to reduce power and on-air time when channel conditions improve and QoS requirements permit (e.g., to save energy, reduce interference, provide LPI)

Protocol Suite for Frequency-Hop Spread Spectrum

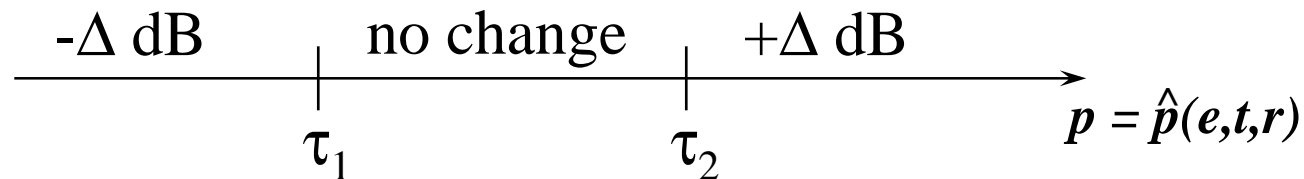
- Channel Access Protocol: RTS/CTS/ACK
- Receiver-directed FH patterns
- Adaptive Transmission Protocol:
 - Use error count (t) and erasure count (e) to adapt code rate and transmit power
 - No power measurements needed
- Adaptive Routing Protocol:
 - Least-resistance routing (LRR) -- a distributed distance-vector routing protocol based on link resistance measures
 - Link resistance derived from metrics that account for link quality, energy consumption, and backlog
 - For multimedia traffic, link resistance depends on message type

Adaptive Transmission Protocol for FH

- Code selection (RS codes) based on erasure count, e

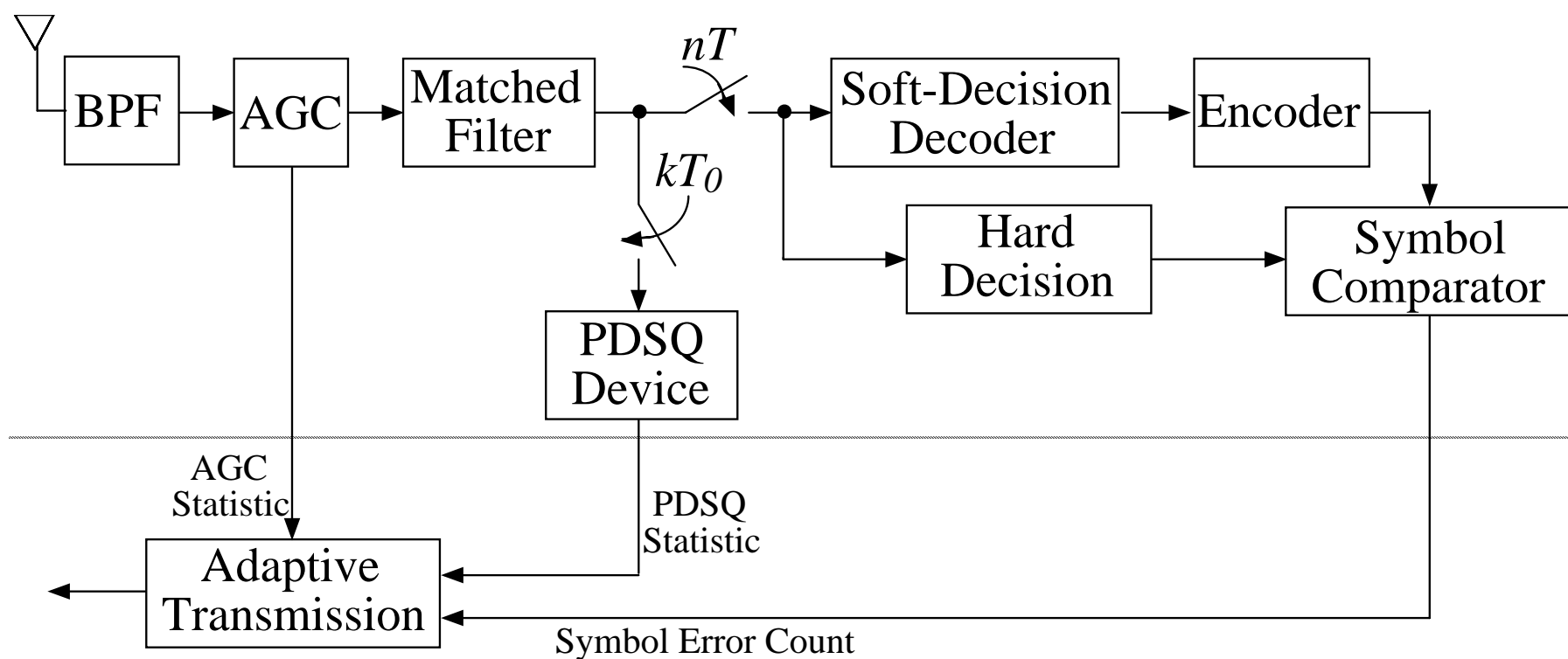


- Power selection based on e , t , and r



No power measurements needed!

Physical-Layer Statistics for Adaptive Transmission in Direct-Sequence Spread Spectrum



Performance Measures

- **Correct packet:** packet that is correct at intended receiver's decoder output
- **Unit of energy:** amount of energy required to transmit a packet at the lowest code rate and highest power (max energy/packet)
- **Throughput Efficiency (link):** Average number of correct packets at decoder output per unit of energy

Channel State Information for FH

Channel State (ρ, λ)

ρ = fraction of the band with interference

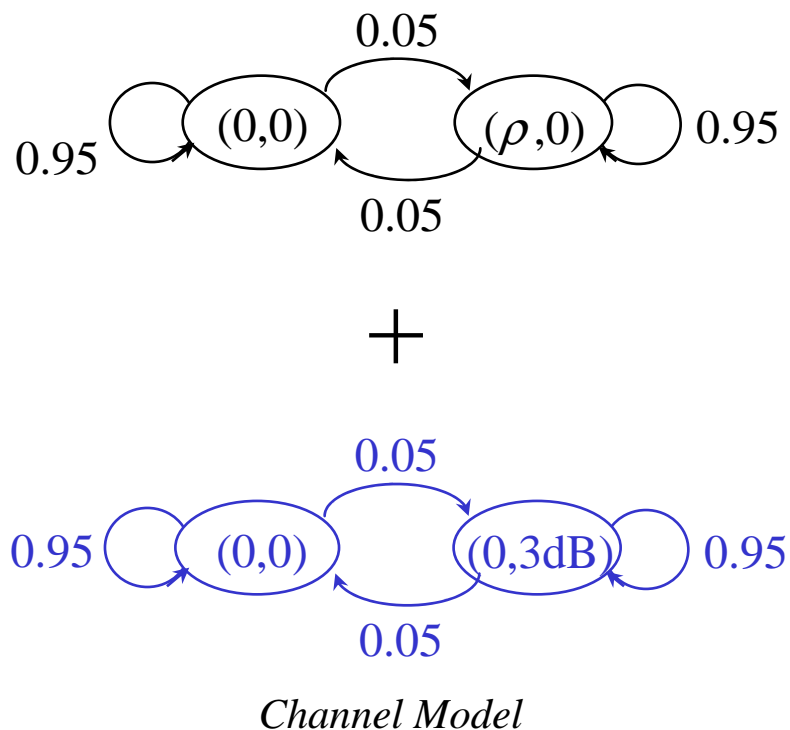
λ = propagation loss

Side Information - information about the channel state that is derived within the communication receiver

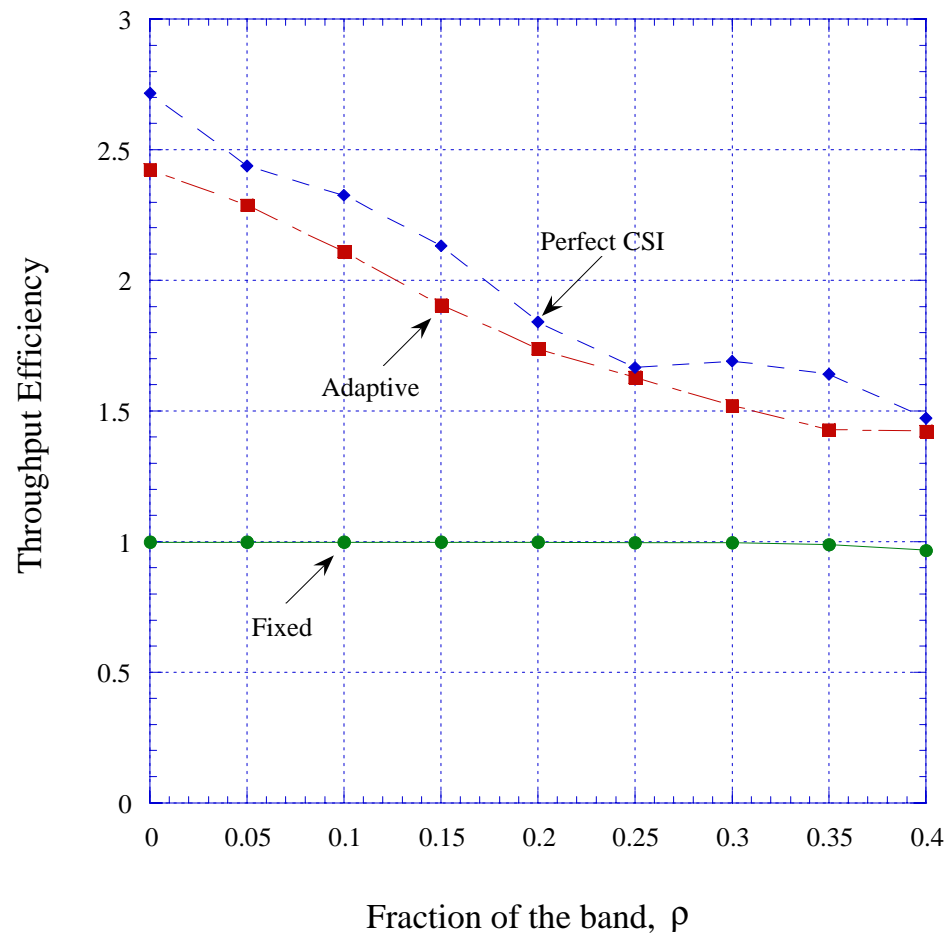
Channel State Information (CSI) - information about the channel state that is supplied from external sources (e.g., special measurement system)

Perfect CSI - exact values of ρ and λ for the previous transmission provided to the communication system

Channel with Intermittent Interference and Time-Varying Path Loss

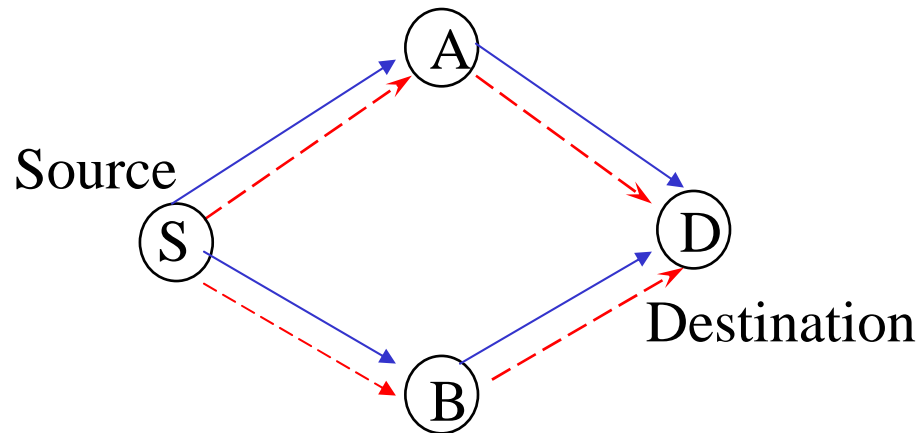


3 power levels, $\Delta = 1.5$ dB



Routing with Adaptive Transmission

Example: A Dynamic Four-Node Network



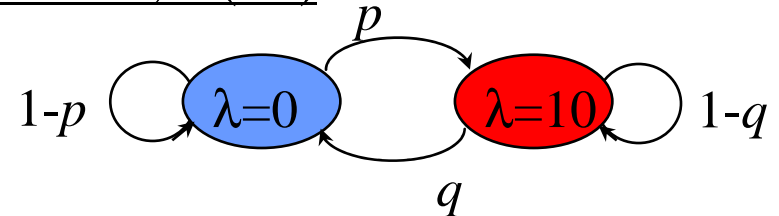
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— 0 dB excess path loss
 - - - 10 dB excess path loss

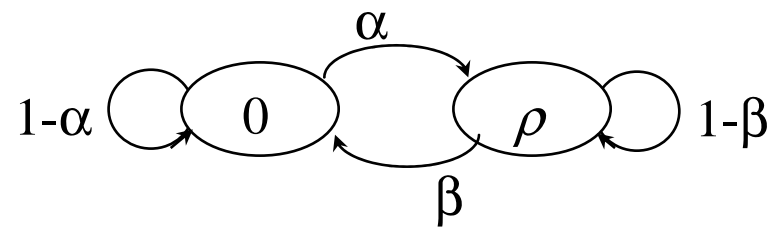
Full power adequate for 10 dB excess loss
 Without adaptation, each link uses full power

Channel State: (ρ, λ)

Path loss, λ (dB):

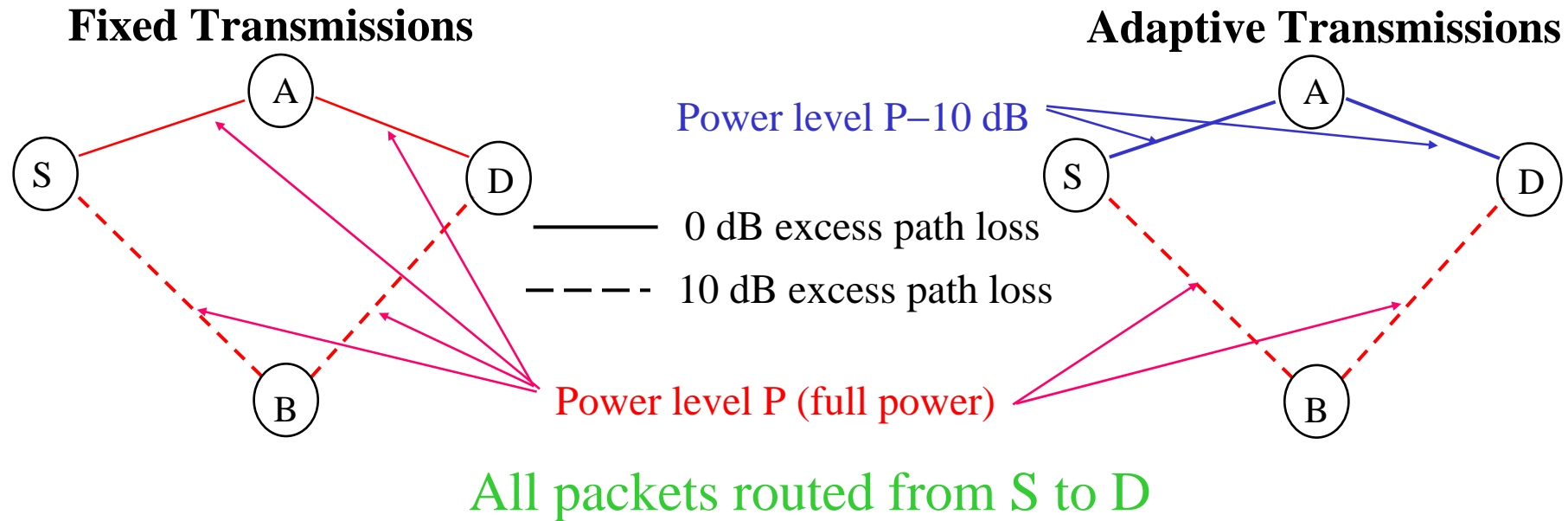


Partial-band interference at terminal B:



ρ = fraction of band for interference at terminal B

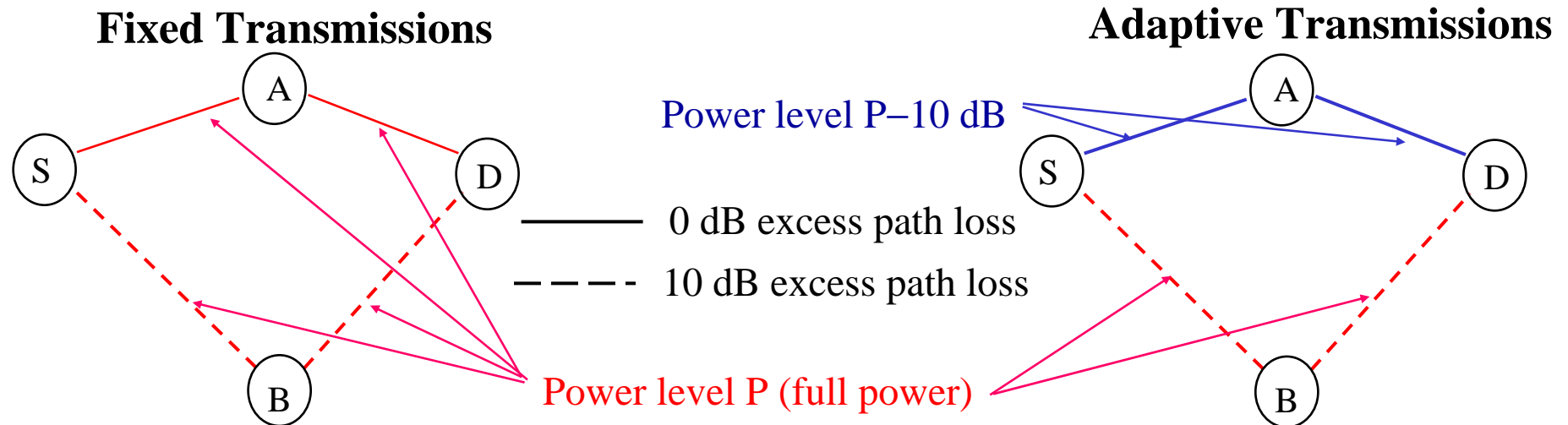
Route Selection, Two Transmission Protocols



With fixed or adaptive transmissions:

- min-hop routing has no preference for upper vs. lower route
- error probability, throughput, delay same for both routes
- QoS routing has no preference for upper vs. lower route

Adaptive Transmission Creates an Opportunity



Adaptive Transmission: enables upper route to use only 1/10 the energy required by lower route; **creates opportunity for routing protocol to save energy**

Least-Resistance Routing with appropriate resistance metric takes advantage of opportunity created by adaptive transmission

Physical-layer information required for routing metrics and adaptive transmission

Resistance Metrics for Generic Traffic

- Quality metric (reception quality)
 - $I(A,B) = (2t + e)/20$ [max redundancy is 20 for code set]
 - # of errors (t) and erasures (e) in previous transmission
- Energy metric (energy consumption)
 - $U(A,B) = P(A,B) r_{\min} / P_{\max} r(A,B)$
 - r_{\min} = min code rate; P_{\max} = max transmitter power
 - $r(A,B)$ = code rate for next transmission $A \rightarrow B$
 - $P(A,B)$ = power for next transmission $A \rightarrow B$

$$LR(A,B) = \alpha_1 I(A,B) + \alpha_2 U(A,B) + c$$

Four Resistance Measures

$$\text{LR}(A,B) = \alpha_1 I(A,B) + \alpha_2 U(A,B) + c$$

Resistance coefficients:

- quality: $\alpha_1 = 4$, $\alpha_2 = 0$, $c = 1$

$$\text{LR}(A,B) = 4 I(A,B) + 1$$

- energy: $\alpha_1 = 0$, $\alpha_2 = 10$, $c = 0$

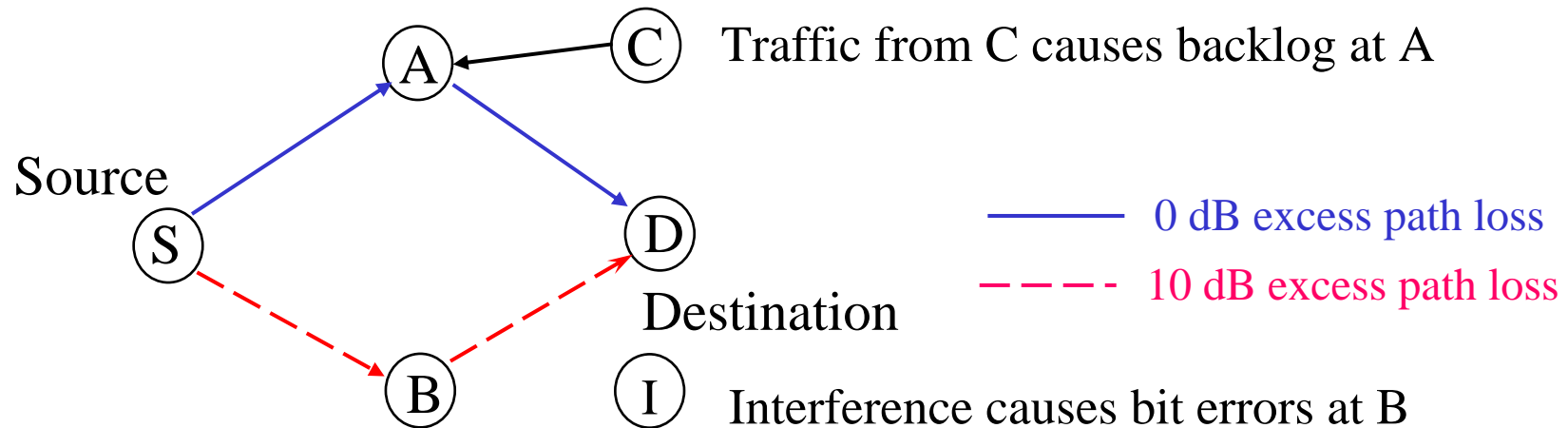
$$\text{LR}(A,B) = 10 U(A,B)$$

- hybrid: $\alpha_1 = 2$, $\alpha_2 = 2.5$, $c = 1$

$$\text{LR}(A,B) = 2 I(A,B) + 2.5 U(A,B) + 1$$

- min-hop: $\alpha_1 = 0$, $\alpha_2 = 0$, $c = 1$; $\text{LR}(A,B) = 1$

Multimedia Considerations in LRR



Voice traffic (previous example) and data traffic from S to D:

- Backlog at A causes delay for route S-A-D, but S-A-D suitable for data traffic; energy conserved if data packets use S-A-D
- Interference causes frame erasures in voice traffic sent over S-B-D, but meets QoS requirements for voice; S-B-D requires more energy
- Approach: Conserve energy for data packets, sacrifice energy conservation for voice packets to meet delay constraint
- Requires interaction among Application/Transport, Network, Link, and Physical Layers

Resistance Measures for Multimedia Traffic

- Each type of traffic routed independently
- Resistance measure tailored to service requirements
 - Emphasize energy consumption for delay-tolerant traffic
 - Emphasize backlog at nodes for delay-sensitive traffic
- MM resistance measures (link $A \rightarrow B$):

$$LR_d(A,B) = 2 I(A,B) + 8 U(A,B) + c_d$$

$$LR_v(A,B) = 4 I(A,B) + W(B) + 2.5 U(A,B) + c_v$$

- Backlog metric for terminal B:

$$W(B) = N_v + \omega N_d$$

N_i = # packets of type i (voice or data) in B's buffer

Performance Measures

Correct packet: packet that is correct at destination receiver's decoder output

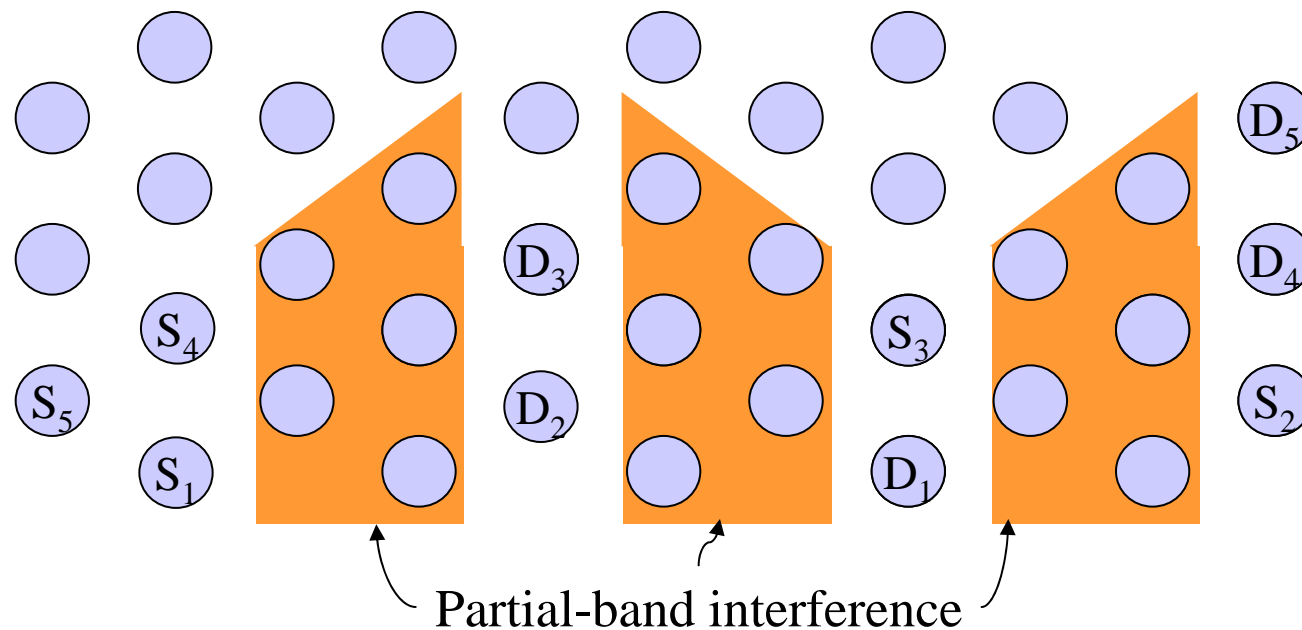
Unit of energy: amount of energy required to transmit a packet at the lowest code rate and highest power (max energy/packet)

- **Throughput Efficiency (network):** Average number of correct packets at decoder output of destination terminal per unit of energy transmitted by all terminals in network

Generic vs. Multimedia Traffic

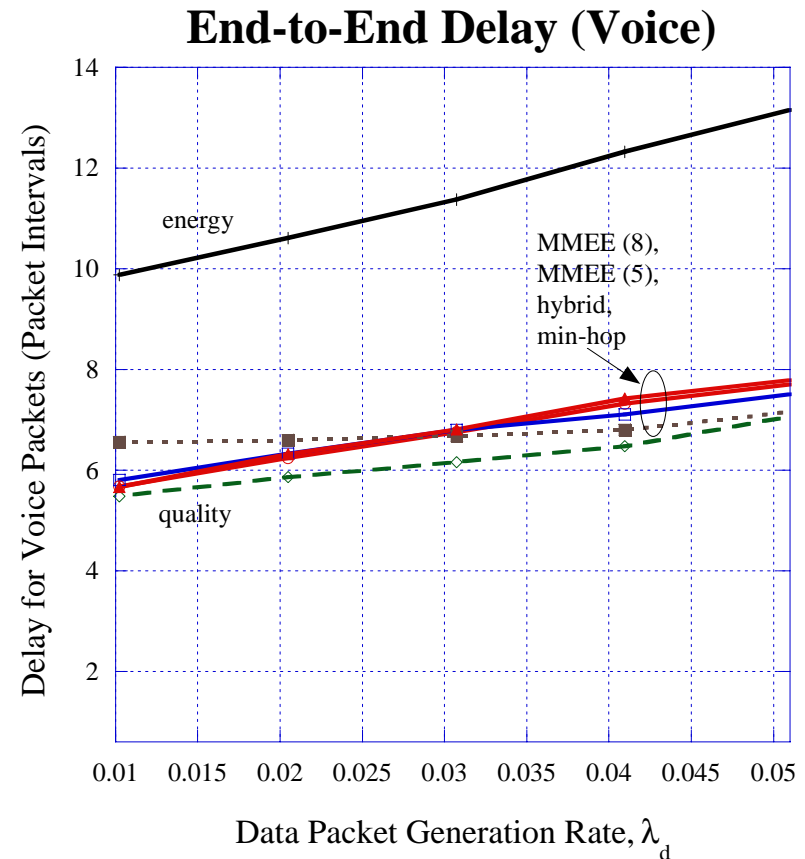
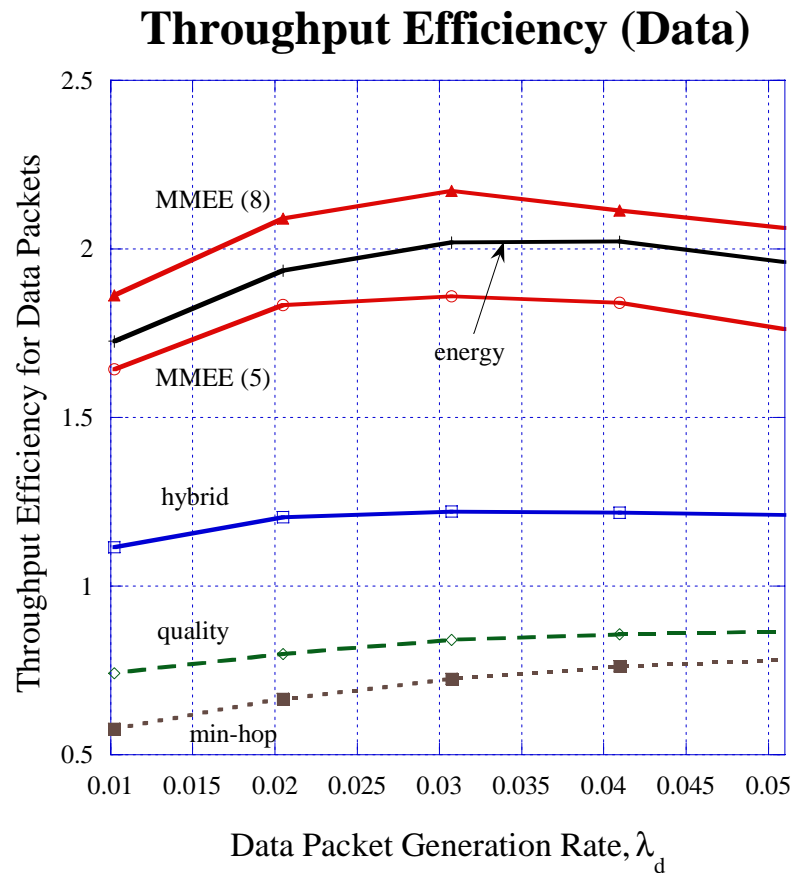
- Simply minimizing energy gives poor performance
- Routing based on link quality and min-hop routing give poor throughput efficiency
- Hybrid quality-energy routing is best compromise for generic traffic
- Emphasize conserving energy for delay-tolerant messages
- Can sacrifice energy conservation for delay-sensitive messages
- Multimedia energy-efficient (MMEE) routing

38-Node Network



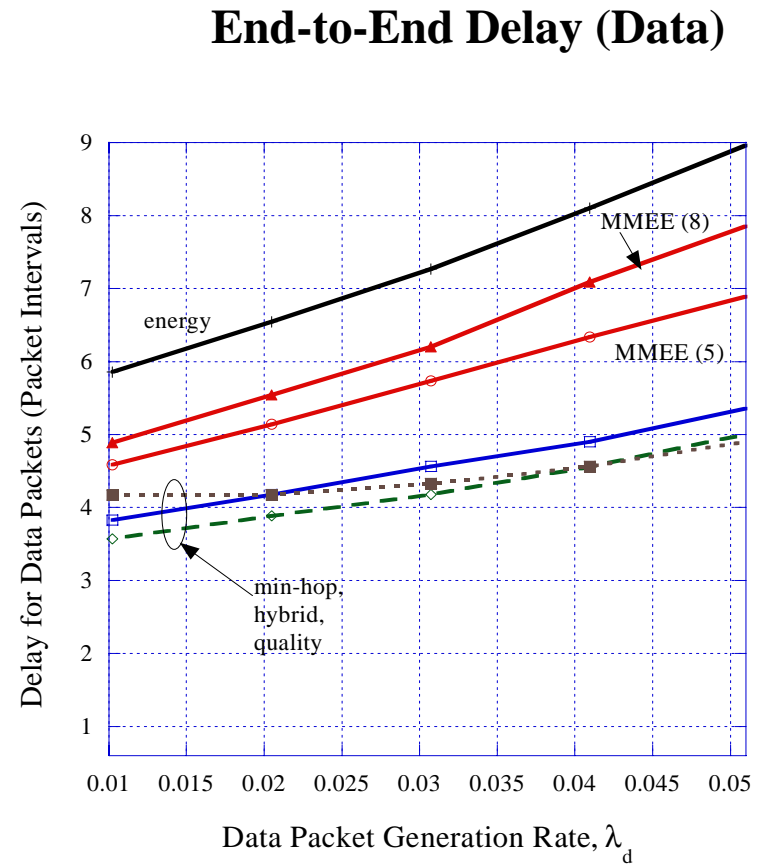
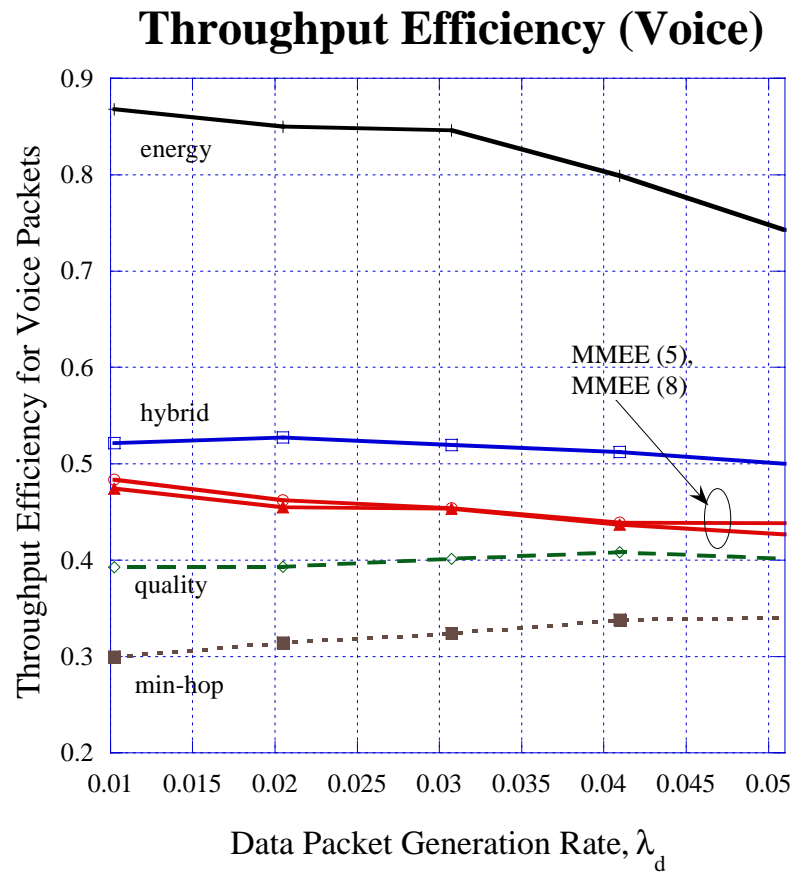
- Node S_i generates voice packets for destination D_i
- Unlabeled nodes generate data packets with random destinations
- Interference occupies 20% of band, affects 15 nodes
- Network uses adaptive transmission (2 code rates, 8 power levels)

Performance of MMEE Routing for 38-Node Network with Multimedia Traffic



Voice traffic generated at fixed rate of 0.01 packets/packet interval

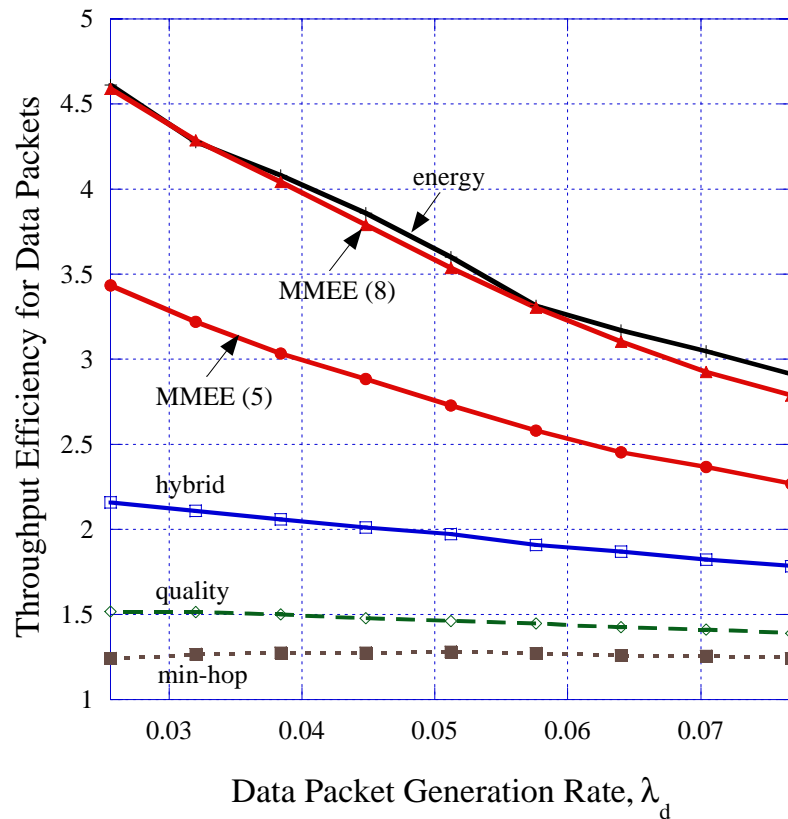
Performance of MMEE Routing for 38-Node Network with Multimedia Traffic



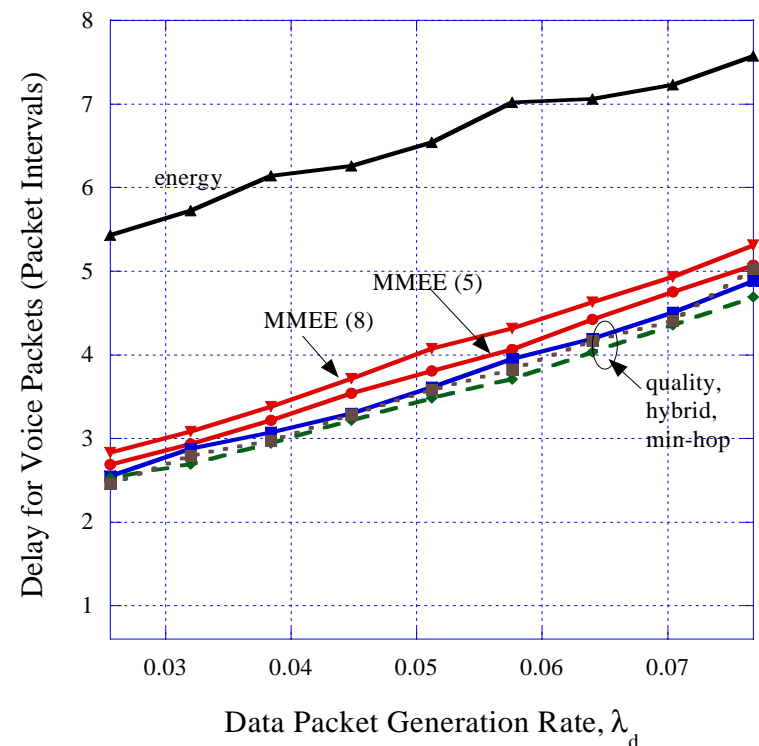
Voice traffic generated at fixed rate of 0.01 packets/packet interval

Performance of MMEE Routing for 65-Node Network with Multimedia Traffic

Throughput Efficiency (Data)



End-to-End Delay (Voice)



- 45 nodes generate data traffic with uniformly random destinations; 10 voice connection pairs
- packet generation rates are in packets per packet interval; voice generation rate is twice λ_d

General Conclusions

- Hybrid quality-energy measure is the best compromise for generic traffic
- MM resistance measures lead to high throughput efficiency for delay-tolerant traffic and low delay for delay-sensitive traffic
- Best resistance measures for multimedia traffic are the MM resistance measures
- Interaction among layers is essential for energy-efficient routing of generic or multimedia traffic